Designing and Analysis of SiGeSn-Based Quantum Wells Integrated With Si Platform for Laser Applications

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***Abstract*-In this work it is showed that compressively strained $Ge_{1-x}Sn_x$/Ge quantum wells (QWs) grown on a Ge virtual substrate are very promising TE mode gain medium. Moreover we show how emission wavelength and polarization can be controlled in $Ge_{1-w}Sn_w/Si_yGe_{1-x-y}Sn_x$ QWs. Demonstration of capabilities of presented QW systems bases on analysis of transverse electric (TE) and transverse magnetic (TM) modes of material gain, which is calculated by 8-band k·p electronic bandstructure.**

I. INTRODUCTION

Group IV semiconductors, like Si and Ge, are widely applied in electronic devices, however their application in light emitters is very limited. The main reason of that is their indirect bandgap nature. For such semiconductors, almost any available electron-hole pair requires phonons in order to preserve momentum in radiative recombination process. This causes significant lowering of the radiative recombination probability in comparing to case when there are a direct bandgap and possible direct optical transitions. Since the nature of bandgap in group IV semiconductors is the main obstacle to the fabrication of light emitters, the bandgap engineering via strains and alloying with other group IV materials is required to make these materials useful for optoelectronic applications.

II. STRUCTURES AND DESIGNING APPROACH

A. Type-I GeSn/Ge Quantum Wells

In order to maintain systematic approach, at first we designed and analysed simplest case, in which there are only Ge and α-Sn included into considered alloys. In our proposition there is a compressively strained $Ge_{1-x}Sn_x$ thin layer grown directly on a Ge substrate or a virtual Ge substrate obtained on an Si platform and capped also with Ge crystal. In Ref. [1] it is showed that such set of materials is compressively strained type-I QW, where $Ge_{1-x}Sn_x$ is material of QW layer and Ge is material of barriers. That kind of structure is the simplest approach which is very widely realized in III-V lasers.

B. Type-I GeSn/SiGeSn Quantum Wells

In second case we expanded in calculations the set of alloys that can be a material of barriers and also proposed one additional layer in order to connect it with Si platform. So, since we kept $Ge_{1-w}Sn_w$ as QW material which can be variously strained, we considered $Si_yGe_{1-x-y}Sn_x$ as unstrained material for barriers grown on lattice matched $Ge_{1-z}Sn_z$ virtual substrate grown on Si substrate. A scheme of proposed structure is showed in Fig. 1.. Since the lattice constant in such heterostructures is determined by the virtual substrate, the built-in strain in thin film can be tuned from tensile ($w < z$) to compressive ($w > z$). Indeed, since the incorporation of Si into GeSn opens up the bandgap, it allows full strain engineering in this material system, which is showed in Ref. [2].

C. Conditions of Usefulness

In order to determine which contents of thin film layer and which thicknesses are reasonable to further gain analysis, basing on 8-band **k·p** model with consideration of L-valley, we performed recognition of critical optic parameters behaviour. As a result of this part of research, we found ranges of contents and thicknesses for which proposed structures forms direct-gap QW and probably are possible to be created from a technological point of view.

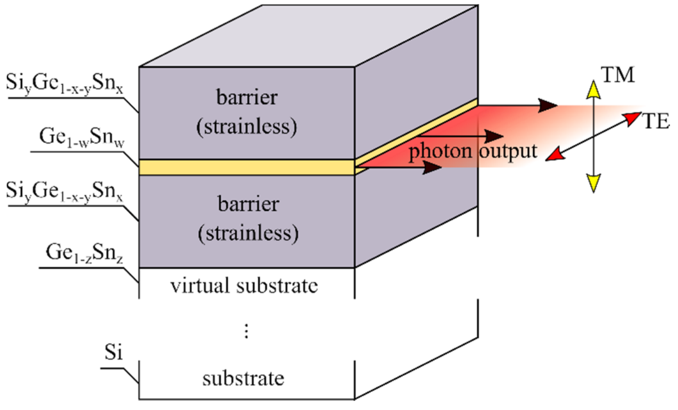

Fig. 1. A scheme of a $Ge_{1-w}Sn_w/Si_yGe_{1-x-y}Sn_x$ QW deposited on a virtual $Ge_{1-z}Sn_z$ substrate. The QW is in the region where there is various strain incorporated so both of light polarization can be generated.

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III. GAIN ANALYSIS

A. Gain Spectra for GeSn/Ge QWs

In GeSn/Ge QWs a TM mode gain values are negligible small in comparison with TE gain values, so TM gain is omitted in analysis. Small values of TM mode gain are result of fact, that in this system there can be only compressive strain incorporated into thin film layer.

Altogether the influences of QW width, α-Sn content in thin film and carrier density on optical gain are analysed. As the one of results of performed work it is presented case for carrier concentration of 6 × 10^{18} cm^{-3} from which some useful information can concluded. The maximal gain should be observed for around 15% of α-Sn in thin film layer. With the increase in GeSn/Ge QW width from 8 nm to 12 nm the material gain increases while the further increase in GeSn/Ge QW width leads. The spectral position of the material gain in 12 nm wide GeSn/Ge QWs can be tuned from around 1.9 µm to around 3.1 µm by an increase in Sn concentration from 10 to 20%.

B. Gain Spectra for GeSn/SiGeSn QWs

In this case both modes TE and TM of optical gain are taken into consideration because, due to virtual substrate there can be incorporated any compressive or tensile strain. In Fig. 2. there is presented a case when barrier is lattice-matched to virtual substrate made of $Ge_{0.85}Sn_{0.15}$. It is clearly visible that in GeSn/SiGeSn QWs, depending on strain, different kind of polarization can be dominating one.

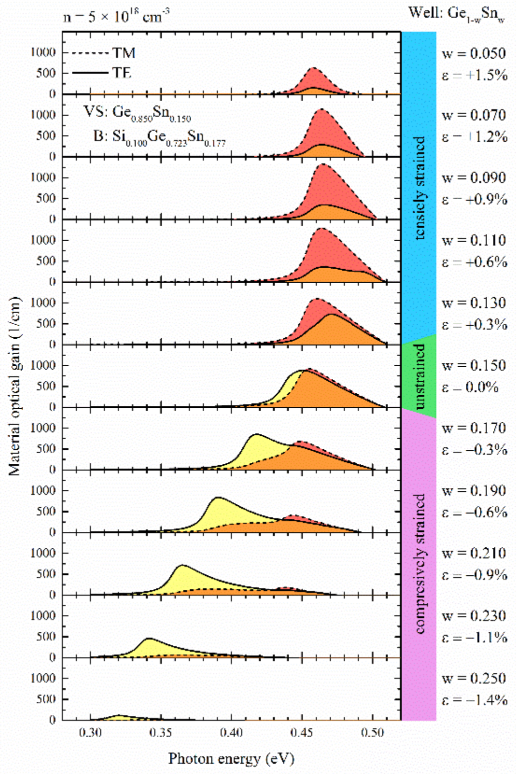

Fig. 2. Spectra of TE (solid lines) and TM (dashed lines) mode of material gain for $Ge_{1-w}Sn_w/Si_{0.1}Ge_{0.723}Sn_{0.177}$ QWs of various α-Sn concentrations (w) grown on virtual $Ge_{0.175}Sn_{0.125}$ substrate

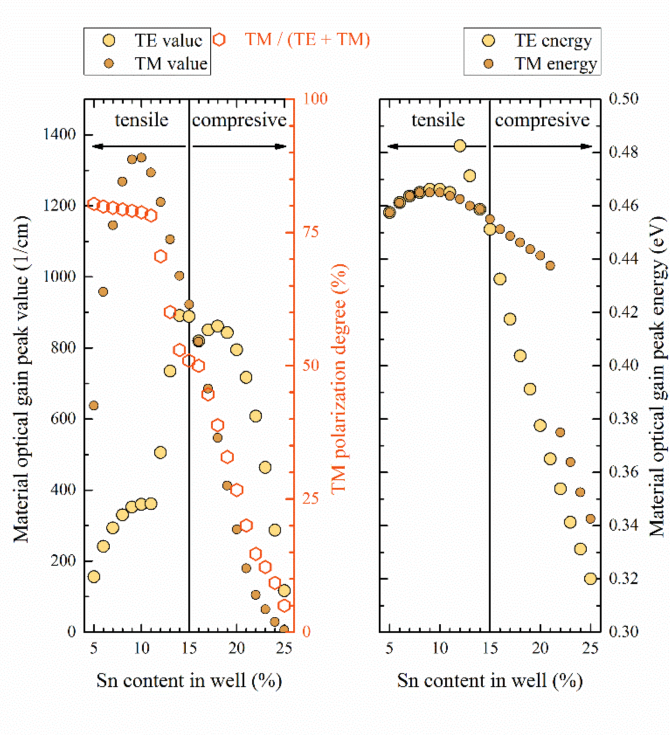

Fig. 3. The peak position for TE and TM mode of material gain (right panel) and the intensity of TE and TM mode at the peak position together with the TM polarization degree (left panel) for $Ge_{1-w}Sn_w/Si_{0.1}Ge_{0.723}Sn_{0.177}$ QWs grown on virtual $Ge_{0.85}Sn_{0.15}$ substrate.

Also here influences of many parameters on optical gain has been analysed. In Ref. [2] is showed how QW width, contents of thin film layer and barriers and carrier density changes or not gain spectra. What more, because GeSn/SiGeSn QWs allows on generating light with both polarisations there is calculated TM polarisation degree defined as the ratio of the intensity of TM mode to the sum of the intensity of TE and TM modes at the given wavelength (peak position of the mode with highest value).

One a final results of this part we performed analysis of gain highest peak value and position and its' TM polarisation degree in α-Sn content function, which is shown in Fig. 3.. In Ref.[2], we also showed how both TM polarisation degree and emitted wavelength can be controlled by incorporating strain, virtual substrate content and thickness of thin film layer.

ACKNOWLEDGMENT

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